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A Review for Numerical Simulation of Vapor Compression Systems

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ABSTRACT

In today's refrigeration and air-conditioning industries, numerical simulation has been widely used for the design and optimization of advanced products. Cost saving and to shorten development cycles of new products are a strong driving force to the development of simulation models. Modeling strategies of HVAC components and system solution techniques vary quite significantly among applications because models are developed with a purpose and are aimed to address specific problems. The objective of this paper is to present an overview of the methodologies and developments of HVAC component modeling and system solvers for steady-state simulations. It can be seen that a number of attempts have been made by researchers to improve the efficiency, robustness and accuracy of simulation models.

1. INTRODUCTION

Worldwide competition is creating increasing pressure to develop more efficient and less costly HAVC equipments. To respond to this pressure, HVAC manufacturers need to have simulation tools which can effectively guide product design and assist in the development of advanced technologies. With the aid of these tools, engineers can evaluate a not-yet-existing product on computers instead of building the real system and running expensive test in the lab.

Vapor compression system simulation can fall into one of two categories: steady-state and transient. Steady-state simulations are often used for performance prediction and product design, while transient simulations are often used for control design and seasonal performance evaluation. An ideal simulation tool should be numerically efficient, robust, accurate and generic. So far, there have been many studies in research of vapor compression system modeling. The purpose of this paper is to present an overview for the modeling methodologies for components and system solution techniques for steady-state simulations.

2. MODELING OF COMPONENTS

In vapor compression systems, compressor, condenser, evaporator and expansion device are four essential components. The emphasis of the extant modeling work has also been on these components.

2.1 Compressor

The compressor is the heart of a vapor compression system and determines system capacity along with the expansion device. Therefore, performance prediction for the compressor is essential for the system level simulation because firstly, the prediction error of refrigerant mass flow rate will be propagated to other component models; secondly, the heat exchangers are typically oversized for the design condition and thus, the accuracy of prediction result largely relies on the mass flow rate.

A number of compressor models have been developed so far. Generally, these compressor models can fall into three categories (Zhao *et al*., 2009): 1) map-based models or black-box models; 2) efficiency-based models or gray-box models and 3) detailed models or white box models.

Map-based models (ARI, 1999; Shao *et al*., 2004) are based on the extensive experimental data from compressor performance test and are most likely to have an accurate performance prediction in terms of mass flow rate, power consumption and discharge temperature. One of the most recognized models in this category is ARI 10 coefficient model which correlates the performance indicators with suction saturation temperature and discharge saturation temperature using ten coefficients (ARI, 1999). Since no physical and geometric parameters are involved in this model, it is very convenient to be used for the system level simulation. However, map-based models are refrigerant dependent if saturation temperatures instead of pressures are used in the correlations. Also, they are only valid over a specific range and do not have a good accuracy for extrapolation. This necessitates developing a map-based model which can capture the physics and at the same time can predict the compressor behavior qualitatively beyond the correlated experimental data range.

Efficiency-based models (Jabardo *et al*., 2002) are based on the ideal compression process and make use of volumetric efficiency and isentropic efficiency via empirical or semi-empirical formulas to predict the compressor performance. Since these models involve more physical fundamentals than the map-based models and thus having better accuracy for the calculation outside the experimental data range. Both map-based models and efficiency-based models typically use the suction state and discharge pressure as inputs to evaluate the compressor performance.

The third category, detailed compressor models (Chen *et al.*, 2002; Chen *et al*., 2004; Rigola *et al*., 2005; Mathison *et al*., 2008), requires many configuration parameters of the compressor, and simulates almost every individual process including the compression process, heat transfer between refrigerant and compression parts, internal refrigerant leakage, and overall energy balance of the compressor, etc. This type of models is useful for the compressor design and not suited for the system level simulation owing to complexity and slow computation speed.

2.2 Heat Exchanger

Though heat exchangers vary significantly with each other in terms of geometries and configurations as well as applications, from the modeling point of view, heat exchanger models can be largely classified into four categories: (a) lumped parameter models, (b) zone model or moving boundary models, (c) distributed parameter models or finite volume models and (d) tube-by-tube models.

Lumped parameter models are the simplest ones. They treat the entire heat exchanger as a single control volume and use an overall UA value to compute the performance of heat exchangers. Thus, the Log-Mean Temperature Difference method or the effectiveness-NTU method can be used. Since these models do not account for phase change and the variation of local refrigerant properties, the accuracy cannot be guaranteed. Lumped parameter models are typically suitable for cycle analysis because more often than not, only qualitative analysis is required under this circumstance.

In moving boundary models, the heat exchanger is subdivided into several phase zones based on the location where phase transition occurs. The main idea of these models is that they make use of the significantly different physical behavior among two-phase flow, superheated gas flow and subcooled liquid flow. Ideally, these models should be capable of handling four regions: supercritical region, superheated region, two phase region and subcooled region. However, in the real case there are very likely only two regions or even one region existing in the heat exchanger. In these models, each region is calculated using lumped parameter approach. An average heat transfer coefficient and an average temperature difference can be evaluated for each region. Obviously, moving boundary models are more accurate than lumped parameter models yet still having favorable computation speed.

In some extent, moving boundary models are a compromise between lumped parameter models and distributed parameter models. In distributed parameter models (Quadir *et al*., 2002; Gut and Pinto, 2003; García-Cascales *et al*., 2010), heat exchanger is divided into a fixed number of segments and the manner that the heat exchanger is divided is independent of phase change. Each segment can use the inlet refrigerant state to evaluate all the thermophysical properties required by the correlations to calculate the heat transfer coefficients and friction factor. Segments can be calculated in sequence along the direction of refrigerant flow. In the simulation, there might be phase transition within a segment. In this case, the segment can be further subdivided based on the location of phase transition to model the different parts of the segment. Experience tells that when increasing the number of segments beyond a certain number, the calculation result will not change much while the computation speed might decrease greatly. Therefore, a decent heat exchanger model of this type should come up with a strategy to pick an appropriate number of segments in order to achieve a tradeoff between accuracy and computation speed.

When modeling an air source plate-fin heat exchanger, the models mentioned above are most likely to treat the entire refrigerant circuit as a long tube. These models more or less are based on some assumptions such as that the refrigerant flow is evenly distributed among each circuit and the air flow is uniform on the fin side. However, these assumptions may result in a significant deviation in calculation for heat exchangers with non-symmetry complex circuits and with non-uniform air flow distribution over the coil face. To accurately simulate heat exchangers of this kind, a tube-by-tube analysis might be needed.

Tube-by-tube models (Domanski, 1999; Liang *et al*., 2001; Jiang *et al*., 2002; Domanski, 2003; Liu *et al*., 2004; Jiang *et al*., 2006; Singh *et al*., 2008) simulate the behavior of the heat exchanger by a rigorous and detailed scheme that considers the influence of the arrangement of refrigerant circuits and tubes on the heat exchanger's performance. These models allow for the analysis of arbitrary tube circuit and refrigerant maldistribution. Undoubtedly, in comparison with other models, tube-by-tube models have the best accuracy and are the most computationally expensive however.

In tube-by-tube models, each tube can either be treated as single control volume, or be divided into several segments to account for the two-dimensional non-uniform air flow distribution across the heat exchanger and the significant change in refrigerant properties and heat transfer coefficients along each tube. A further sub-dividing-segment approach can be also used in order to address phase transition if a segment experiences phase change.

There have been a few well established heat exchanger simulation and design tools in the public domain. Domanski (1999 and 2003) introduced a software package EVAP-COND for a finned-tube evaporator and condenser, which is based on a tube-by-tube approach and offers many features like refrigerant maldistribution through circuits of different lengths and one-dimensional air flow maldistribution. This package was later successfully used in an optimization system called ISHED (intelligent system for heat exchanger design), which uses domain knowledge based structure modifying operator and symbolic learning method, to optimize evaporator circuitry for cases involving non-uniform air distribution (Domanski *et al.*, 2004; Domanski and Yashar, 2007).

Liu *et al.* (2004) developed a general steady state model for a fin-and-tube heat exchanger based on graph theory, which accounts for refrigerant maldistribution through a flexible circuitry arrangement and accounts for heat conduction between tubes as well. Their model applies conservation of energy to a given control volume, starting with guessed outlet states for air and refrigerant as well as guessed wall temperatures. In an iterative process for every control volume of the heat exchanger, wall temperature, outlet refrigerant state, and outlet air state are obtained such that energy is conserved for the control volume. For the overall heat exchanger calculation, an alternative iteration method is used to decouple the calculation of energy conservation equations and momentum conservation equations. This model was used to optimize refrigerant circuitry of heat exchanger for maximizing heat load by employing an improved genetic algorithm (Wu *et al*., 2008).

Jiang *et al.* (2006) presented a general purpose simulation and design tool for air-to-refrigerant heat exchanger. In this model, each tube is divided into several segments. This allows the user to model two-dimensional air flow maldistribution on coil face. Furthermore, a genetic algorithm is integrated into this model for single and multiple-objective optimization design of heat exchanger (Jiang, 2003). As a further step to Jiang's work, Singh *et al*. (2009) expanded the capability of Jiang et al.'s model to be able to simulate heat exchangers with arbitrary fin sheets which encompasses variable tube diameters, variable tube locations, variable tube pitches, internal and external jagged edges, variable number of tubes per bank and variable location of fin cuts. In addition, Singh *et al*. (2008) introduced two models termed as "resistance model" and "conduction model" to account for heat conduction along the fins. To decrease computational cost, the resistance model ignores the effect of air heat transfer coefficient and has been demonstrated to be an acceptable simplification.

Microchannel heat exchangers (MCHXs) are drawing more attention these days because of compactness and higher heat transfer performance in comparison with conventional finned-tube heat exchangers. The modeling of MCHXs has been studied by some researchers. Yin *et al*. (2001) developed a finite volume model to predict the performance of a CO_2 cross flow microchannel gas cooler. Kim and Bullar (2001) presented a detailed multi-slab microchannel evaporator model. In their study, the evaporator was subdivided into several segments and each segment is calculated by mass balance and energy balance equations. In Jiang's model (2003), both conventional MCHXs and serpentine heat exchangers are addressed by finite volume method. Asinari *et al*. (2004) introduced a sophisticated numerical model for microchannel gas cooler that can take into account the effect of thermal conduction along the fins and the walls of tubes. Their model shows that the longitudinal conduction in fins, the transverse and the longitudinal conduction in tubes give negligible effects on the total heat flow and on the temperature field. Shao *et al*. (2009) introduced a port-by-port microchannel condenser model to investigate the heat transfer and pressure drop of R-290 in a serpentine heat exchanger. Their model has four calculation levels. The heat exchanger is divided into serpentine tubes. Each serpentine tube is divided into micro channels (ports). Each port is divided into elements along the refrigerant flow direction. Each element is a simple cross-flow arrangement between portions of the refrigerant and air streams, and the heat conduction between each element is considered. In their model, refrigerant and air maldistribution are taken into account as well.

2.3 Expansion Device

In vapor compression systems, capillary tubes, orifices and valves are used as the throttling device to regulate the refrigerant mass flow. The fluid through these expansion devices experiences a drastic change in thermophysical properties and the mechanism behind is very complex. Based on the modeling approach, expansion device component models mainly tend to fall into two big groups: correlation-based models and distributed parameter models.

Correlation based models (Stoecker, 1983; Kim *et al*., 1994; Kim and O'Neal, 1994; ASHRAE, 2002; Choi *et al*., 2003; Li *et al*., 2004; Park *et al*., 2007) tend to calculate the mass flow rate given the inlet condition and outlet pressure. These models use simple equations and have a good accuracy in the range of regression. However, the downside of these models is the unpredictable accuracy of extrapolation. When the fluid condition is out of the regression range, the predicted results using these models are usually doubtful. Furthermore, these models tend to be refrigerant-dependent, the existing correlations might work well for some refrigerants, but not for others (Zhang and Ding, 2001).

Compared with correlation based models, distributed parameter models are more worthy to investigate from a research point of view. As a matter of fact, a number of studies have been focusing on the modeling of capillary tubes and short tube orifices (Kim and O'Neal, 1995; Zhang and Ding, 2001; García-Valladares *et al*., 2002; Bassiounay and O'Neal, 2004; Zhang and Yang, 2005; Yang and Zhang, 2005; Madsen *et al*., 2005; Agrawal and Bhattacharyya, 2008). According to the assumption of whether the two-phase flow is homogeneous or not, distributed parameter models can be further classified into homogeneous flow models (Bansal and Rupasingh, 1998) and separated flow models (Wong and Ooi, 1996; Ding, 2007). Homogenous flow models assume that the slip ratio between liquid phase and vapor phase is unity, and the void fraction can be analytically evaluated. While separated two-phase flow is considered, the void fraction needs to be estimated using semi-empirical equations.

There are generally four regions that exist along the capillary tube including subcooled liquid region, metastable liquid region, metastable two-phase region and equilibrium two-phase region (García-Valladares *et al*., 2002). The existence of metastable flow regions actually increases the mass flow because it results in the delay of flash point and as a consequence, the overall resistance offered by the capillary tube is reduced. In capillary tube models however, the metastable flow is usually neglected due to its unpredictability. Studies show that the resulted error without considering metastable flow is acceptable, and the predicted result can be readily corrected by other means (Ding and Zhang, 2001; Ding, 2006).

Typically, when modeling the capillary tube, it is assumed that no heat transfer occurs during the refrigerant flowing through the capillary tube, and the stagnation enthalpy of the refrigerant is considered to be conserved throughout. However, in some applications this is not the case. For instance, in household refrigerators and automobile air-conditioners, capillary tube is often in thermal contact with the suction line to achieve better system performance. To consider the heat transfer when refrigerant flows through the capillary tube, non-adiabatic capillary tube models are required.

Non-adiabatic capillary tube models (Chen and Gu, 2005; Agrawal and Bhattacharyya, 2007; Hermes *et al*., 2008) differ from the adiabatic ones in the two main aspects. One is that for non-adiabatic models, the calculation needs to account for the heat transfer across the tube wall in order to evaluate the refrigerant leaving state for each segment. This greatly increases model complexity. The other aspect is that in the adiabatic analysis, the entropy increases during the throttling process and it can be used as a criterion to judge whether the flow is choked or not. In the non-adiabatic models however, the entropy might decrease due to heat rejection and therefore, it cannot be used to determine whether the choked flow occurs or not. In this situation, that the local velocity of the refrigerant equals the local sonic velocity is used to judge the occurrence of choked flow (Chen and Gu, 2005).

3. SYSTEM SOLUTION TECHNIQUES

Component models are the pillars of performing the system level simulation, the job of the system solution scheme is to combine all the component models together according to the relationship between component parameters to calculate the system performance given certain constraints and under certain operation conditions.

A steady-state simulation provides details regarding the system performance at a set of design points and describes how the system will perform at off-design conditions (Winkler, 2009). Typically, a simulation in design mode has different system constraints from an off-design simulation. For the design mode, the subcooling leaving the condenser and the superheat leaving the evaporator often need to be specified, whereas the refrigerant charge needs to be fixed in off-design mode. Steady-state simulation tools are extensively used for system and component design and for performance prediction, and therefore they are inherently required to be numerically efficient, robust and accurate. Since the accuracy on the system level is largely dependent upon the accuracy of component models, the main responsibility of the system solution scheme should emphasize on efficiency and robustness such that users can build up their confidence to the simulation tool.

The unknown variables in the system solver are typically fluid-related state information. Other parameters such as power consumption and capacity can be calculated instantaneously once all fluid state information is obtained. Generally, there are two approaches in which these variables are solved (Winkler, 2009): 1) successive approach where a variable is solved prior to moving on the next unknown variable; 2) simultaneous approach, which uses a non-linear equation solver to simultaneously solve all unknown variables.

Depending on the system configuration, successive approach (Davis and Scott, 1976; Hiller and Glicksman 1976; Ellison and Creswick, 1978; Tassou *et al*., 1982; Domanski and Didion, 1983; Fischer and Rice, 1983; Domanski and McLinden, 1992; Robinson and Groll, 2000; Koury *et al*., 2001; Joudi and Namik, 2003; Sarkar *et al*., 2006) usually utilizes more than one nested loop to conduct the system level iterations. This approach typically works well for system with relatively simple configurations. Once the system cycle gets complicated, it is not easy to come up with an efficient iteration scheme, especially for multistage cycles with flow mixing and splitting. In addition, successive approach is not flexible due to the fact that a small modification to the system cycle might result in a major change in the solution scheme. For instance, the solution scheme for a basic cycle with four components might be completely different from that for the cycle with a suction line heat exchanger. However, this approach has the merit of being robust and efficient. One of the underlying reasons is that the iterative variables required in this approach are typically less than the number of unknowns required in the simultaneous approach. Another reason is since the solution scheme is usually aimed to address a specific system configuration, it is relatively convenient to optimize the solution scheme. To demonstrate how the successive approach works, an example of solution algorithm (Ding and Zhang, 2001) for a basic cycle that uses capillary tube as the expansion device is presented in Fig. 1.

To create a generic simulation tool that can handle arbitrary system cycles, a component-based solution scheme needs to be used. This method makes it possible to decouple the system solver with the component models. In other words, the calculation details of the component models are completely transparent to the system solver. The system solver only needs the connection information among components to make sure that the mass balance, momentum balance and energy balance are satisfied. Once the boundary conditions are provided by the system solver, the component models will take care of the calculation of their own. After all the component models are executed, the fluid information will be passed back to the system solver to be used to construct system level residual equations. The order of running theses component models actually does not matter as long as all the unknown variables have guess values at the very first beginning of iterations to avoid mathematical failures.

The most noticeable advantage of this component-based solution scheme is its generality and flexibility. One does not have to modify the system solver if a different system cycle needs to be simulated. To realize this functionality, a simultaneous solving method needs to be considered. Among various non-linear equation solvers, Newton-Raphson and quasi-Newton equation solvers (Broyden's method, Powells' method) are the most popular ones because of their fast convergence capability. Winkler *et al*. (2007) compared three different system solvers among which the junction solver is a good exemplary that can fall into the category of simultaneous solving methods.

As mentioned previously, simultaneous approach (Parise, 1986; Almedia *et al*., 1990; Jolly, *et al*., 1990; Herbas *et al*., 1993; Rossi, 1995; Hwang and Radermacher 1998; Corberan *et al*., 2000; Corberan *et al*., 2002; Richardson *et al*., 2002; Richardson *et al*., 2004; Shao *et al*., 2008) requires more unknown variables because these unknowns are simultaneously solved and are treated as being independent of each other when constructing system residual equations. This increases computational cost. For successive approach however, the order of the component models needs to be carefully chosen in order to reduce the number of iteration variables. For instance, the compressor model can be executed first to obtain the refrigerant mass flow that is needed for heat exchanger models.

There are currently a variety of vapor compression system simulation tools. As early as in 1983, The Oak Ridge National Laboratory (ORNL) introduced a Heat Pump Design Model (Fischer and Rice, 1983) to aid engineers in the design of vapor compression systems. The tool remains in use today by design engineers and has undergone a number of enhancements over the years. This tool can do design and off-design analysis, but is only capable of air-to-air heat pump simulations for the system with fixed four component.

Thermal Systems Research and Modeling (IMST) of the Universidad Politécnica de Valencia developed and released Advance Refrigeration Technologies (ART) in 2002 (Corberan *et al*., 2002). The simulation tool is only capable of simulating the basic four component cycle; however various accessories can be added to the system such as piping, liquid-suction line heat exchanger, and a four-way valve. The simulation tool allows users to select different types of heat exchanger, compressor, expansion device models all of which vary in level of detail. The Hybrid method is used to solve the unknown variables simultaneously in the program.

The National Institute of Standards and Technology (NIST) offers a vapor compression cycle design program called CYCLE_D (Domanski *et al*., 2003). CYCLE_D only is capable of simple cycle analysis and is not intended to be a detailed vapor compression simulation tool.

Rossi (1995) developed a detailed steady-state simulation model, ACMODEL. The program requires all the input parameters to be provided by using batch files. Though the simulation tool is constructed in a modular, object-oriented format, the component library is limited to a single finite difference based heat exchanger model and a single ARI map-based compressor model (Shen *et al*., 2004).

Richardson *et al*. (2002) introduced a generic component-based simulation tool that is capable of simulating four different cycle types including basic cycle with four components, basic cycle with suction line heat exchanger, two-stage flash cycle and two-stage split cycle. A multi-objective genetic algorithm is integrated into this tool for system optimization. The Junction Solver is introduced as being the system solver and is designed to provide complete flexibility in designing vapor compression system configurations. However, in this solver, heat exchanger models need to implement the inlet/outlet pressure boundary condition. Boundary pressure based heat exchanger models require an additional iterative procedure to determine the refrigerant mass flow rate thus increasing the computational effort while decreasing the model's robustness. Winkler *et al*. (2008) presented a new solver called Enthalpy Marching Solver (EMS). Compared with the Junction Solver, EMS needs fewer unknown variables and thus being faster and more robust. Unfortunately, it is very difficult for EMS to handle refrigerant splitting and merging. Therefore, a truly generic, robust and efficient solver needs to be developed.

4. CONCLUDING REMARKS

Vapor compression system simulation tools play an important role in the design of HVAC equipment. They have combined the disciplines of thermodynamics and heat transfer. As an enhancement option, they can also combine the disciplines of acoustics and cost that are not presented in this paper. The tools can be used by engineers to predict the interactive effects of component performance, size on the system design and its operational characteristics. The capability to predict these effects can enhance the ability of engineers to make wise decision in the design process and thereby shortening the design cycle.

Although the extant work has made great progress in the area directed at improving efficiency, generality and robustness of the system solver, there are very few simulation tools that are capable of simulating complicated system configuration very effectively. Moreover, though there are simulation tools that claim to be able to handle arbitrary system configurations, the robustness and numerical efficiency of these tools have not been demonstrated clearly. It is still worthy to devote time and effort to develop a truly generic, robust and efficient simulation tool.

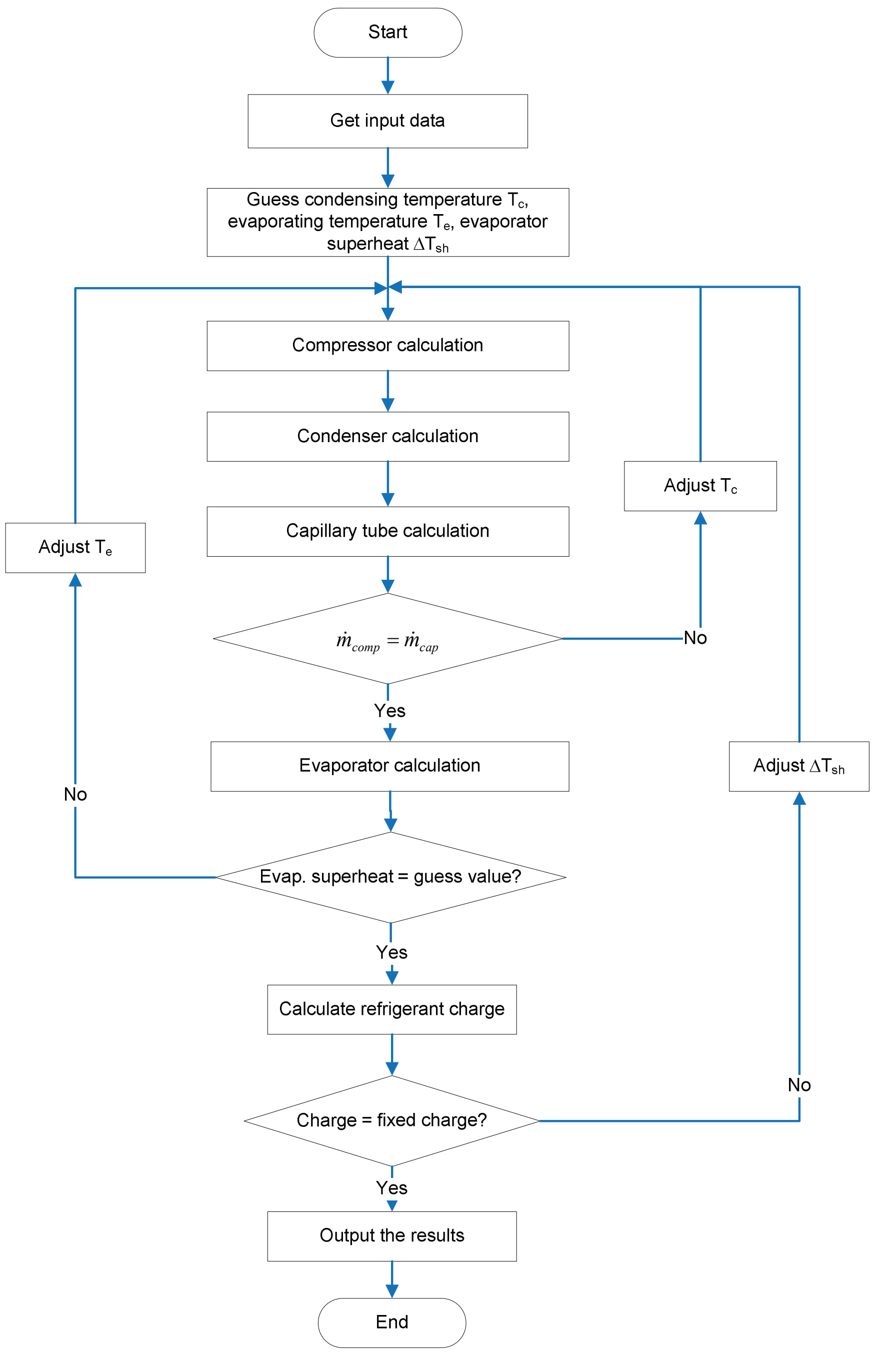

Fig. 1: Solution scheme of a basic cycle with capillary tube in the off-design mode using successive approach (Ding and Zhang, 2001)

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